CONTROL OF A REDUNDANT FLEXIBLE MANIPULATOR ON A SPACE PLATFORM

○Tadashi KOMATSU*
Vinod J. MODI†
Clarence W. DE SILVA†

**Dept. Mechanical Engineering, Kanto Gakuin University*
Mutsuurahigashi 1-50-1, Kanazawa, Yokohama, Kanagawa, 236-8501 Japan
email:komatsu@kanto-gakuin.ac.jp
†Dept. Mechanical Engineering, The University of British Columbia
2324 Main Mall, Vancouver, B.C. Canada V6T 1Z4

ABSTRACT—*Space manipulators have several features uncommon to ground-based robots. They are highly flexible, are often mobile, and have a degree of redundancy. In this paper, we propose a trajectory control method for a redundant flexible space manipulator with slewing and deployable links on a space platform. This method consists of manipulator's tip position feedback with transposed Jacobian and local vibration control. We newly derived Jacobian for a flexible manipulator considering link deformation. Also, we realized link vibration control with local torque feedback at each joint. Simulation results show the effectiveness of this method. We used in-plane dynamics developed in our group. This dynamics consists of an order N algorithm, based on the Lagrangian approach, to simulate the planar dynamics of an orbiting manipulator with arbitrary number of slewing and deployable flexible links.*

KEYWORDS: Space Robot, Flexible Arm, Space Station, Dynamics, Vibration Control, Deployable Links

INTRODUCTION

Several space robots have been designed as well as many are proposed for development. These include the Space Shuttle based Remote Manipulator System, a variety of free-flying space robots and the Space Station Remote Manipulator System. Also, many studies have been reported concerning dynamics and control of such robots[1-7]. In general, space robot systems consist of large scale and lightweight structures. For example, the Space Shuttle Manipulator system is 16 m long. They should be light extremely to reduce the launch cost and to be used in a no gravity environment. Therefore, it is necessary to control link vibration for precise trajectory control. Also, we can not operate space robots on the ground. If we do that, structures of a robot are broken by their weight. Moreover, it is difficult to realize a no gravity environment on the ground. For this reason, simulation plays very important role for research and development of space robots.

In this paper, we consider a control law for a space platform-based large flexible manipulator system(Fig.1). This robot can traverse the platform with a mobile base and perform a variety of tasks, for example, handling of payloads. The two-unit robot has not only slewing but also deployable links. This robot will be one of important space robots in the near future. The system has several advantages:

(a) reduced dynamical coupling leading to relative simple equations of motion and inverse kinematics;
(b) reduced number of singular configuration for the same number of degrees of freedom;
(c) case of avoidance.

On the other hand, we have to consider flexibility of space structures. That is, link vibration can easily occur in this system, because a space manipulator and a platform consist of long and lightweight links in general. At the same time, vibration of a manipulator also influences platform attitude. Therefore, we need vibration control of a manipulator. Moreover, we have to consider redundancy of a manipulator when controlling manipulator's tip along a trajectory.

We propose a real-time control law for a both redundant and flexible manipulator. There have been few studies for real-time control of such a manipulator. This method also gives little influence to attitude of a space platform. The effectiveness of our method was shown by simulations using dynamics in an orbit.

DYNAMICS

In this section, we will describe dynamics of the system for simulations. The general nature of the model presented here allows for a serial manipulator consisting of an arbitrary number (N) of flexible units. Each unit consists of two links: one free to slew while the other is permitted to deploy and retrieve(Fig.1). We use the in-plane dynamics which was developed by Caron et al.[8]. This formulation was derived using the non-recursive and the *O*(N) approach. Therefore, the computational time and memory requirements are reduced considerably. In this section, we explain this model. Figure 2 shows coordinate systems for a multibody system. Robot motion is constrained in the orbital plane. F_0 is the inertia reference frame fixed to the Earth. F_r is an orbital reference frame. F_i is a reference frame attached to the i^{th} body. $\mathbf{r}_i$ is a position vector of the elemental mass dm_i with respect to F_i. $\mathbf{f}_i$ is the displacement of the mass element, located at $\mathbf{r}_i$, due to body flexibility. Figure 3 presents description of the body-fixed frame F_i relative to the preceding frame F_{i-1}. $\mathbf{l}_{i-1}$ is the length of the $(i-1)^{th}$ body. $\mathbf{d}_i$ is translation of the frame F_i from the tip of the $(i-1)^{th}$ body. $\mathbf{e}_i$ is displacement of the frame F_i caused by the elastic deformation of the $(i-1)^{th}$ body.

For modeling of flexibility, the elastic deformation modes were used. The platform is assumed to behave as a free-free Euler-Bernoulli beam. Modules of the manipulator are modeled as cantilever beams with tip masses.

Generalized coordinates $\mathbf{q}$ consist of true anomaly of the system (θ), inertial orientation of the frame F_i (ψ_i), a vector containing the time dependent generalized coordinates describing the elastic deformation of the i^{th} body (δ_i)、rotation of the frame F_i caused by the control action of the actuator located at the i^{th} joint (α_i), and $\mathbf{d}_i$, ℓ_i .

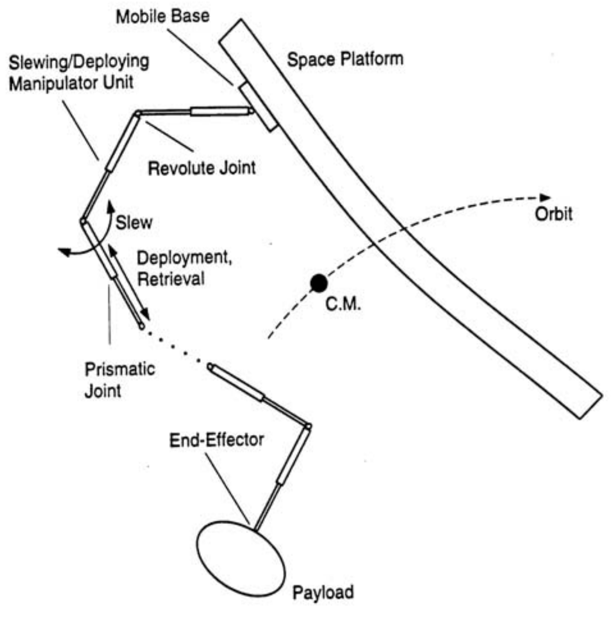

Fig. 1. A Schematic Diagram of the Mobile Flexible Deployable Manipulator, Based on a Space Platform, Considered for Study.

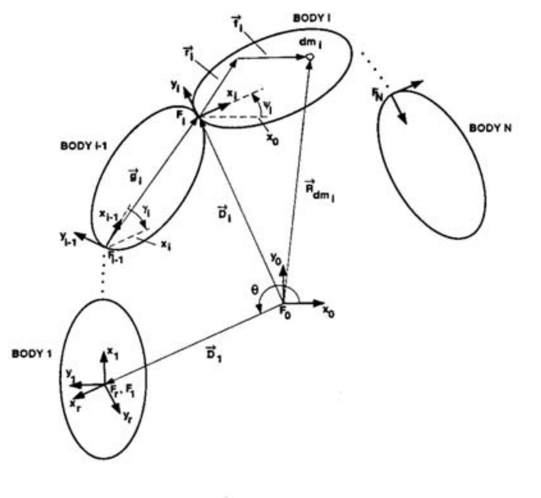

Fig. 2. A Schematic Diagram of a Multibody System in Chain Topology with Coordinate Frames and Vectors used to Define an Elemental Mass.

After calculating system kinetic energy T, gravitational potential energy Vg, strain energy Ve and energy dissipation R_d, the equation of motion can be obtained using the Lagrangian procedure

$$\mathbf{M}\ddot{\mathbf{q}} + \dot{\mathbf{M}}\dot{\mathbf{q}} - \frac{1}{2}\frac{\partial(\dot{\mathbf{q}}^{T}\mathbf{M}\dot{\mathbf{q}})}{\partial \mathbf{q}} + \frac{\partial \mathrm{Vg}}{\partial \mathbf{q}} + \frac{\partial \mathrm{Ve}}{\partial \mathbf{q}} + \frac{\partial \mathrm{R}_d}{\partial \dot{\mathbf{q}}} = \mathbf{Q}^{\mathbf{d}}\mathbf{u} + \mathbf{P}^{\mathbf{c}}\mathbf{\Lambda} \tag{1}$$

where $\mathbf{u}$ is generalized force, Λ is a vector of Lagrange multipliers, $\mathbf{Q}^{d}$ and $\mathbf{P}^{c}$ are coefficient matrices and $\mathbf{M}$ is mass matrix.

TRAJECTORY CONTROL METHOD

In this section, we propose the control approach consisting of the following two methods. The first is the trajectory control of the manipulator's tip in a redundant system. Here, we propose transposed Jacobian method for a flexible manipulator to reduce the computational effort and adapt to the change of an outer environment quickly,

$$\mathbf{u_T} = \mathbf{J}^{T}\{\mathbf{G_1}(\mathbf{X_d} - \mathbf{X_m}) + \mathbf{G_0}(\dot{\mathbf{X}}_\mathbf{d} - \dot{\mathbf{X}}_\mathbf{m})\} \tag{2}$$

where $\mathbf{X}_d$ is a target trajectory, $\mathbf{J}^T$ is the transposed Jacobian. In conventional method, $\mathbf{J}$ was Jacobian for rigid arms. But in our method, $\mathbf{J}$ was derived considering not only rigid arm kinematics but also link deformation. $\mathbf{G}_0$ and $\mathbf{G}_1$ are control gain matrices, and $\mathbf{u}_T$ is a vector of target torques.

The method can realize position control. But there are many configurations at one position of the manipulator's tip because of redundancy, and there are no constraint conditions about the configuration. Therefore, vibration control is not quite effective with only this method.

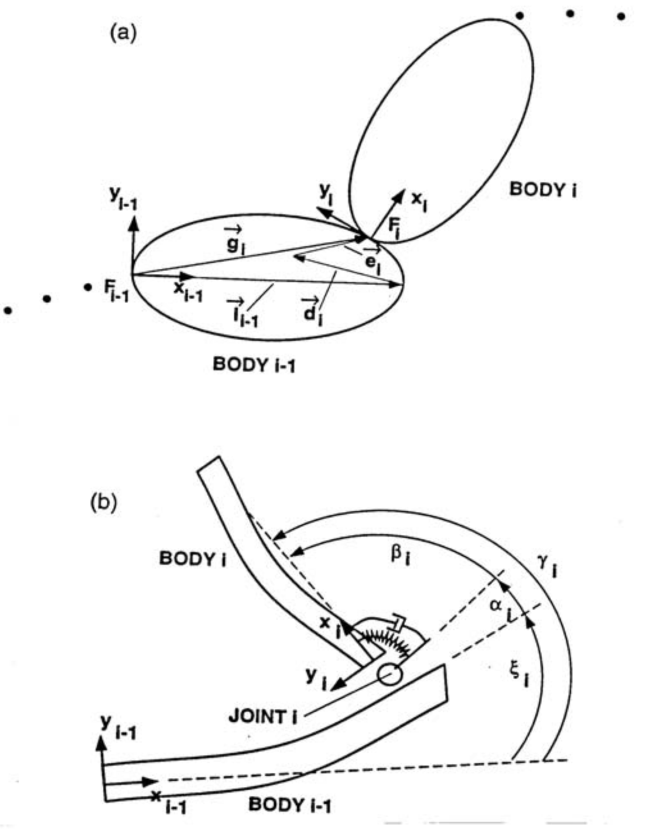

Fig. 3. Description of a Body-fixed Frame Relative to the Preceding Frame; (a)Position (b)Orientation.

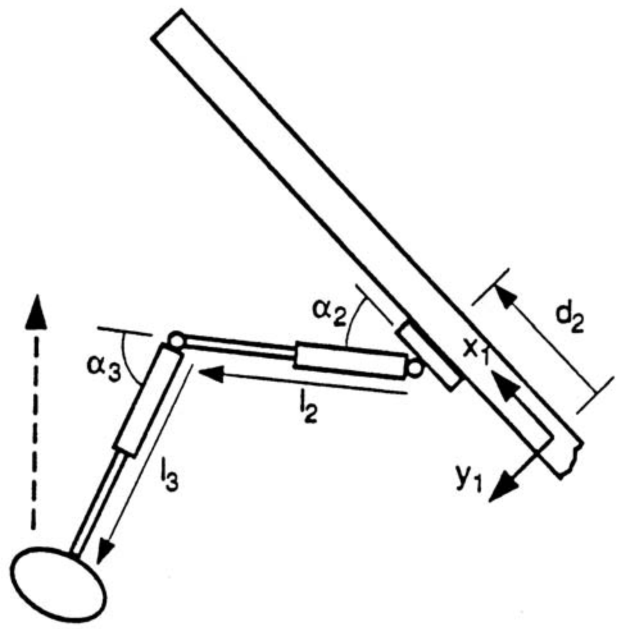

Fig. 4. Orbiting Space Platform with a Two-module Manipulator.

Next, we added vibration control method to Eq.(2) using local torque feedback method,

$$\mathbf{u} = \mathbf{G_2}(\mathbf{u_T} - \mathbf{T}) - \mathbf{G_3}\dot{\mathbf{q}}_\mathbf{m} \tag{3}$$

where **T** is force/torque at joints, $\mathbf{G_2}$ and $\mathbf{G_3}$ are control gains, and $\mathbf{q}_m$ is a vector consisting of α_i and ℓ_i. This method is effective for dynamical coupling between a manipulator and a space platform, also when the length of manipulator's links changes.

SIMULATIONS

Effectiveness of the proposed control method was investigated. We did simulation study using Eq.(1). For the numerical simulation, a space platform, supporting a mobile manipulator, orbiting around the Earth was considered. The numerical data used in the simulation are summarized as follows: Number of bodies N is 3, i.e. the space platform with a two-module manipulator(Fig.4). The orbit is circular at an altitude of 400 km with a period of 92.5 min. The geometry of the platform is cylindrical with axial to transverse inertia ratio of 0.005, mass=120,000 kg, length=120 m, and flexural rigidity(EI_p)=5.5×10^8 Nm^2. The manipulator revolute joint mass = 20 kg, moment of inertia = 10 kgm^2, and stiffness(k)=1.0×10^4 Nm/rad. The manipulator links(slewing and deployable) have a cylindrical geometry with axial to transverse inertia ratio of 0.005, mass=200 kg, middle length=7.5 m, and flexural rigidity(EI_s, EI_d)= 5.5×10^5 Nm^2. The platform is initially oriented along the local vertical, i.e. pitch angle ψ =0, and is not controlled by actuators. Mobile base was fixed at the center of a platform. Only the first mode was used in modeling of flexibility.
The acceleration vector $\ddot{\mathbf{q}}$ was integrated numerically using Gear's method in 1.0×10^{-8} seconds interval, which is well suited for stiff systems of ordinary differential equations. We used FORTRAN77 to write a program with a UNIX workstation.
In the following simulations, the longitudinal elastic deformation of the bodies is neglected, as well as the dynamics of the mobile base. Furthermore, the manipulator is not supporting any payload.
As the first case, a dynamical simulation was done to investigate the response of a two-unit manipulator. The manipulator's shoulder joint (α_2) was moved from 50 deg to 45 deg in three seconds and elbow joint (α_3) held at the initial angle of 30 deg. Figure 5 shows results. The end-effector vibrated at 0.06Hz with a deflection of 1.4 m at a 15 m long manipulator's tip and 1.5 cm at an upper arm. Its natural frequency is very low and interrupts to the controllable frequency band of a manipulator. In this model, a tip deflection is affected by not only link flexibility but also joint flexibility.
The second case examines that trajectory control along a straight line is implemented using the proposed control method. Figure 4 shows initial configuration and direction of the target trajectory. Here a sine-ramp profile is adopted for prescribed maneuvers. It assures zero velocity and acceleration at the beginning and end of the maneuver, thereby reducing the structural response of the system. The maneuver time history considered for x and y directions is as follows:

$$q_{sj}(\tau) = (\Delta q_{sj}/\Delta\tau)\{\tau - (\Delta\tau/2\pi)\times\sin[(2\pi/\Delta\tau)\tau]\} \tag{4}$$

where q_{sj} is the target trajectory, Δq_{sj} is its desired variation, τ is the time, and $\Delta\tau$ is the time required for maneuver. The manipulator's tip moved for 5 m in 27 seconds along a dotted line in Fig.4. Figure 6 shows results. The maximum error becomes only 1 cm at a 15 m long manipulator's tip. The reason is that the system could keep stable under the high control gain condition by the vibration control. Link vibration occurs and has high frequency character. But its amplitude becomes of *O*(mm) and is small compared with the case of Fig.5. The maneuver also excites, slightly, the platform vibration. But its deformation became smaller than manipulator's tip deflection.
The third case involves that, under the same conditions with the second case, the manipulator is controlled using only tip position feedback, that is, employing only $\mathbf{J}^T\{-\}$ term in Eq.(2) for **u**. Figure 7 shows results. Deflection was similar to that for the case of Fig.6. But the maximum tip position error became 16 cm. It is sixteen times bigger than the case of Fig.6. This is mainly caused by that we could not select big control

gains $\mathbf{G_0}$ and $\mathbf{G_1}$. If we select the same control gains with the second case, the system becomes unstable. This means that vibration control is necessary for precise trajectory control of a flexible arm.
These results of three cases show that accurate position control can be realized with our proposed method. Through these results, the platform vibration is excited by the maneuver. But even the platform tip vibration, which persists, has amplitude of only ± 0.2 mm.

STABILITY

Next we will describe about stability of the manipulator system with the proposed control method. First, we will derive Hamilton's equation of motion to use the theorem of Lyapunov. We introduce the slack variables for convenience[9]. Assume that the rank of Jacobian matrix $\mathbf{J}$ is n(<2N-2) and $X_1,\ldots,X_n$ are independent variables. The vector of task-oriented coordinates $\mathbf{X_m}$ is written as

$$\mathbf{X_m} = (X_1,\ldots,Xn)^T = \mathbf{f}(\mathbf{q_m}) \tag{5}$$

The vector of slack variables $\mathbf{X_s}$ is written as

$$\mathbf{X_s} = (X_{n+1},\ldots,X_{2N-2})^T = \mathbf{f_s}(\mathbf{q_m}) \tag{6}$$

which satisfies a condition,

$$\det\left[\frac{\partial \mathbf{f_e}}{\partial \mathbf{q_m}}\right] = \det[\mathbf{J_e}] \neq 0 \tag{7}$$

where the vector $\mathbf{f_e}=(\mathbf{f}^T, \mathbf{f_s}^T)$ and matrix $\mathbf{J_e}$ is related with $\mathbf{J}$ as

$$\mathbf{J_e} = \begin{bmatrix} \dfrac{\partial \mathbf{f}}{\partial \mathbf{q_m}} \\ \cdots \\ \dfrac{\partial \mathbf{f_s}}{\partial \mathbf{q_m}} \end{bmatrix} = \begin{bmatrix} \mathbf{J} \\ \cdots \\ \dfrac{\partial \mathbf{f_s}}{\partial \mathbf{q_m}} \end{bmatrix} \tag{8}$$

Then the equation of motion for $\mathbf{X_e}^T=(\mathbf{X_m}^T,\mathbf{X_s}^T)$ is written as

$$\frac{d}{dt}\begin{bmatrix} \mathbf{X_m} \\ \mathbf{X_s} \end{bmatrix} = \begin{bmatrix} \left(\dfrac{\partial H}{\partial \mathbf{p_m}}\right)^T \\ \left(\dfrac{\partial H}{\partial \mathbf{p_s}}\right)^T \end{bmatrix} \tag{9}$$

$$\frac{d}{dt}\begin{bmatrix}\mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix} = -\begin{bmatrix}\left(\frac{\partial H}{\partial \mathbf{X_m}}\right)^T\\ \left(\frac{\partial H}{\partial \mathbf{X_s}}\right)^T\end{bmatrix} + (\mathbf{J_e}^T)^{-1}\mathbf{u} \tag{10}$$

where vector $\mathbf{p_m}$ is a generalized momentum for $\mathbf{X_m}$ and $\mathbf{p_s}$ is for $\mathbf{X_s}$. Now we consider an asymptotic stabilization with respect to ($\mathbf{X_m}^T$, $\mathbf{p_m}^T$, $\mathbf{p_s}^T$). Control $\mathbf{u}$ is set as

$$\begin{aligned}\mathbf{u} &= \mathbf{G_2}[\mathbf{J}^T\{\mathbf{G_1}(\mathbf{X_d} - \mathbf{X_m}) + \mathbf{G_0}(\dot{\mathbf{X}}_\mathbf{d} - \dot{\mathbf{X}}_\mathbf{m})\} - \mathbf{T}] - \mathbf{G_3}\dot{\mathbf{q}}_\mathbf{m}\\ &= \mathbf{G_2}\mathbf{J}^T\mathbf{G_1}(\mathbf{X_d} - \mathbf{X_m}) - \mathbf{G_2}\mathbf{J}^T\mathbf{G_0}\dot{\mathbf{X}}_\mathbf{m} - \mathbf{G_2}\frac{\partial V_{em}}{\partial \mathbf{q_m}} - \mathbf{G_3}\dot{\mathbf{q}}_\mathbf{m}\end{aligned} \tag{11}$$

where $\dot{\mathbf{X}}_\mathbf{d} = \mathbf{O}$.

Substituting $\mathbf{u}$ of Eq.(11) into Eq.(10), we obtain

$$\begin{aligned}\frac{d}{dt}\begin{bmatrix}\mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix} = -\begin{bmatrix}\left(\frac{\partial H}{\partial \mathbf{X_m}}\right)^T\\ \left(\frac{\partial H}{\partial \mathbf{X_s}}\right)^T\end{bmatrix} &+ (\mathbf{J_e}^T)^{-1}\mathbf{G_2}\mathbf{J}^T\mathbf{G_1}(\mathbf{X_d} - \mathbf{X}_m) - (\mathbf{J_e}^T)^{-1}\mathbf{G_2}\frac{\partial V_{em}}{\partial \mathbf{q_m}}\\ &- (\mathbf{J_e}^T)^{-1}\mathbf{G_2}\mathbf{J}^T\mathbf{G_0}\dot{\mathbf{X}}_\mathbf{m} - (\mathbf{J_e}^T)^{-1}\mathbf{G_3}\dot{\mathbf{q}}_\mathbf{m}\end{aligned} \tag{12}$$

Since terms

$$-(\mathbf{J_e}^T)^{-1}\mathbf{G_2}\mathbf{J}^T\mathbf{G_0}\dot{\mathbf{X}}_\mathbf{m} - (\mathbf{J_e}^T)^{-1}\mathbf{G_3}\dot{\mathbf{q}}_\mathbf{m}$$

can be written as

$$-(\mathbf{J_e}^T)^{-1}(\mathbf{J}^T G_2\mathbf{G_0}\mathbf{J} + \mathbf{G_3})\mathbf{J_e}^{-1}\dot{\mathbf{X}}_\mathbf{e}$$

assuming G_2 is a scalar, we can regard it as the damping force which is derived from the dissipation function

$$\dot{\mathbf{X}}_\mathbf{e}(\mathbf{J_e}^T)^{-1}(\mathbf{J}^T G_2\mathbf{G_0}\mathbf{J} + \mathbf{G_3})\mathbf{J_e}^{-1}\dot{\mathbf{X}}_\mathbf{e}$$

in the space of $\mathbf{X_e}$. We consider the asymptotic stability of the position by means of the linearized system of Eqs.(9) and (12). Linearizing these equations at ($\mathbf{X_m}^T$,$\mathbf{X_s}^T$,$\mathbf{p_m}^T$,$\mathbf{p_s}^T$)=($\mathbf{X_d}^T$,$\mathbf{X_{sd}}^T$,$\mathbf{O}^T$,$\mathbf{O}^T$), we obtain

$$\frac{d}{dt}\begin{bmatrix}\delta\mathbf{X_m}\\ \delta\mathbf{X_s}\end{bmatrix}=\left[\mathbf{J}_e\mathbf{M_e}^{-1}\mathbf{J_e}^T\right]\begin{bmatrix}\mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix}=\begin{bmatrix}\mathbf{M_{e11}} & \mathbf{M_{e12}}\\ \mathbf{M_{e12}}^T & \mathbf{M_{e22}}\end{bmatrix}\begin{bmatrix}\mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix} \tag{13}$$

$$\frac{d}{dt}\begin{bmatrix}\mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix}=-\begin{bmatrix}G_2\mathbf{G_1} & \mathbf{O}\\ \mathbf{O} & \mathbf{O}\end{bmatrix}\begin{bmatrix}\delta\mathbf{X_m}\\ \delta\mathbf{X_s}\end{bmatrix}-\left[(\mathbf{J_e}^T)^{-1}(\mathbf{J}^TG_2\mathbf{G_0}\mathbf{J}+\mathbf{G_3})\mathbf{J_e}^{-1}\right]\begin{bmatrix}\delta\dot{\mathbf{X}}_\mathbf{m}\\ \delta\dot{\mathbf{X}}_\mathbf{s}\end{bmatrix} \tag{14}$$

where the kinetic energy T_m of a manipulator is written as

$$T_m=\frac{1}{2}\dot{\mathbf{q}}_\mathbf{m}{}^T\mathbf{M_e}\dot{\mathbf{q}}_\mathbf{m} \tag{15}$$

defining

$$\left(\delta\mathbf{X_m}^T,\delta\mathbf{X_s}^T\right)=(\mathbf{X_m}^T-\mathbf{X_d}^T,\mathbf{X_s}^T-\mathbf{X_{sd}}^T)$$

and $\mathbf{X_{sd}}^T$ is an appropriate vector. It may be easily seen that the vector $\delta\,\mathbf{X_s}$ can be pulled out from the system of Eqs.(13) and (14). Consequently, we obtain the reduced system of Eqs.(13) and (14) as follows,

$$\frac{d}{dt}\begin{bmatrix}\delta\mathbf{X_m}\\ \mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix}=\begin{bmatrix}\mathbf{O} & \mathbf{M_{e11}} & \mathbf{M_{e12}}\\ -G_2\mathbf{G_1} & -(\mathbf{J_e}^T)^{-1}(\mathbf{J}^TG_2\mathbf{G_0}\mathbf{J}+\mathbf{G_3})\mathbf{M_e}^{-1}\mathbf{J_e}^T & \\ \mathbf{O} & & \end{bmatrix}\begin{bmatrix}\delta\mathbf{X_m}\\ \mathbf{p_m}\\ \mathbf{p_s}\end{bmatrix} \tag{16}$$

If we differentiate the Hamiltonian $\overline{H}$ of the manipulator system

$$\overline{H}=T_m+V_m+G_2V_{em}+\frac{1}{2}(\mathbf{X_m}-\mathbf{X_d})^TG_2\mathbf{G_1}(\mathbf{X_m}-\mathbf{X_d}) \tag{17}$$

along the solution trajectory of the system Eq.(16), we obtain

$$\begin{aligned}\dot{\overline{H}}&=-(\mathbf{p_m}^T,\mathbf{p_s}^T)\mathbf{J}_e\mathbf{M_e}^{-1}(\mathbf{J}^TG_2\mathbf{G_0}\mathbf{J}+\mathbf{G_3})\mathbf{M_e}^{-1}\mathbf{J_e}^T\begin{pmatrix}\mathbf{p_m}\\ \mathbf{p_s}\end{pmatrix}\\ &=-\dot{\mathbf{X}}_\mathbf{e}{}^T(\mathbf{J_e}^{-1})^T(\mathbf{J}^TG_2\mathbf{G_0}\mathbf{J}+\mathbf{G_3})\mathbf{J_e}^{-1}\dot{\mathbf{X}}_\mathbf{e}\end{aligned} \tag{18}$$

Since the set $[(\delta\mathbf{X_m}^T,\mathbf{p_m}^T,\mathbf{p_s}^T);\dot{\overline{H}}=0;\text{i.e.},(\mathbf{p_m}^T,\mathbf{p_s}^T)=\mathbf{O}^T]$ does not contain the entire trajectory except $(\delta\mathbf{X_m}^T,\mathbf{p_m}^T,\mathbf{p_s}^T)=\mathbf{O}^T$, we can conclude that the system (17) is asymptotically stable.

It should be noted that the vector $\mathbf{X_s}$ is introduced only for convenience of the above argument. The vector $\mathbf{X_s}$ converges to a certain position, with which we need not be concerned.

Though the asymptotic stability of the redundant system is assured only for the linearized system in this section, global asymptotic stability can be assured for the nonlinear system of Eqs.(9) and (10), proved that the boundedness of the vector $\mathbf{X_s}$ can be assumed. It is rigorously proved by the result of literature.

CONCLUSIONS

The paper presents dynamical simulations of a redundant flexible space manipulator on a space platform. We used an effective mathematical model developed for studying the in-plane dynamics and control of a general, flexible, space-based manipulator. We proposed a trajectory control method for a redundant flexible space manipulator with slewing and deployable links. The proposed task-oriented coordinate control method seems suitable to sensor feedback control because the real data from each sensor can be directly used as a feedback input. The effectiveness of this method was shown by simulations. The future study will aim at adapting this method to a variety of different trajectories.

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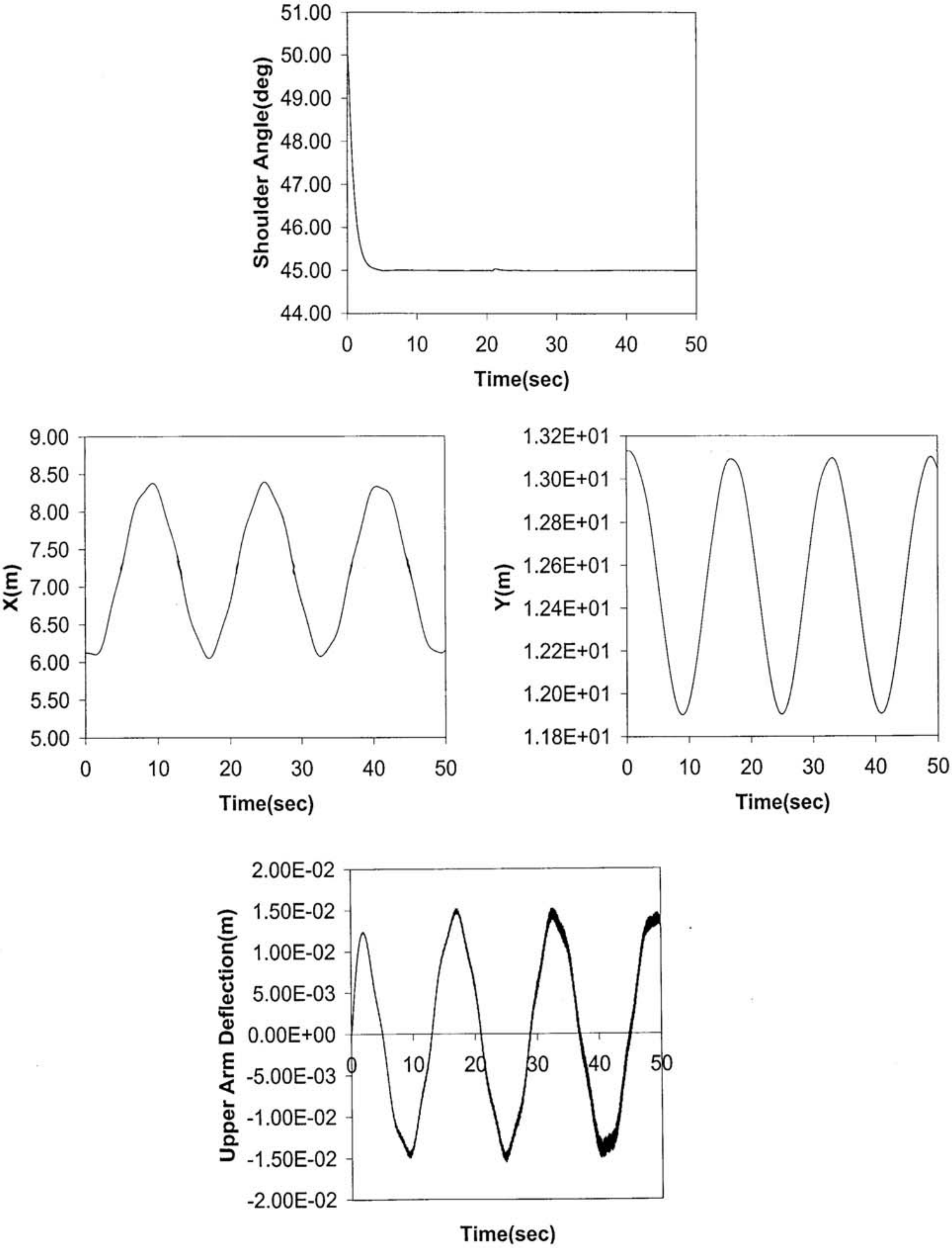

Fig. 5. **Time Histories of the End-effector and Arm Deflection for a Step Maneuver of the Shoulder Joint.**

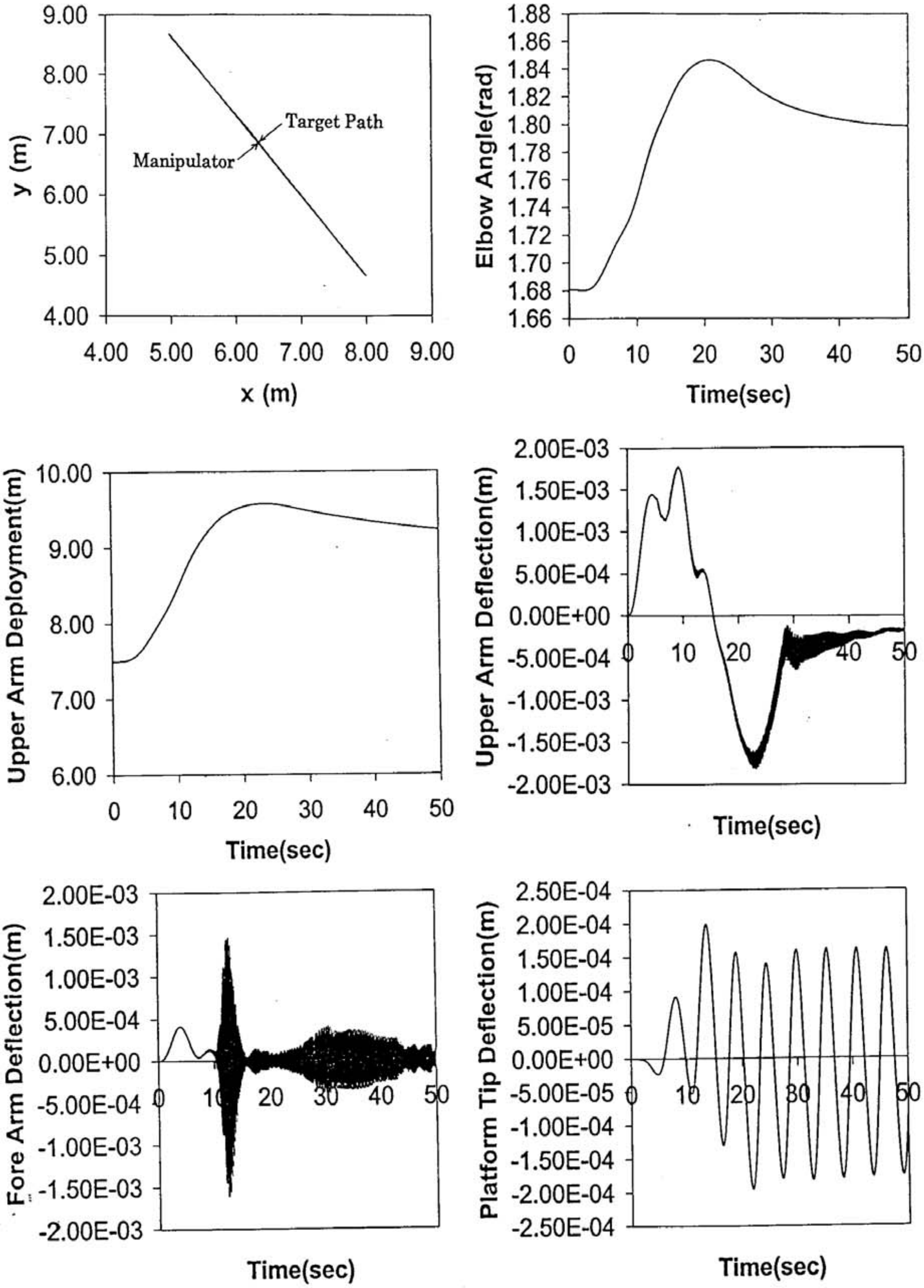

Fig. 6. Time Histories of a Space Robot System During Tracking of a Straight Line Trajectory Using the Proposed Control Method.

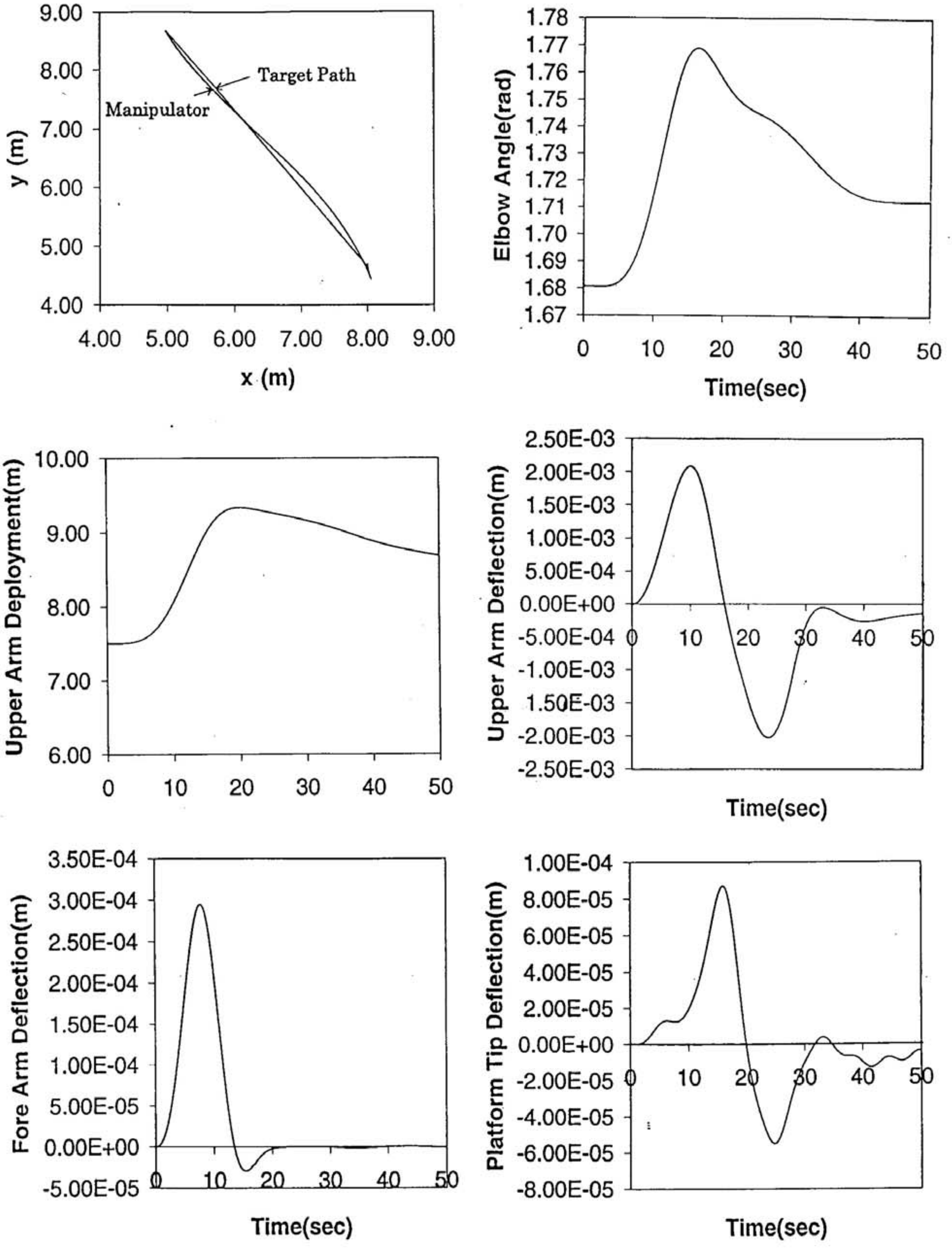

Fig. 7. System Dynamics During Trajectory Tracking Using Only the Position Feedback (Straight Line).